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RESEARCH MEMORANDUM

COMPONENT PERFORMANCE INVESTIGATION OF J71 EXPERIMENTAL TURBINE

V - EFFECT OF THIRD-STAGE SHROUDING ON INTERNAL-FLOW CONDITIONS OF J71-97 TURBINE

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

A negligible effect on stage efficiency and a small improvement in the flow conditions through the third stage were observed when the J71 experimental turbine was modified to include shrouding of the third-stage rotor.

INTRODUCTION

The NACA Lewis laboratory is currently conducting a study of high-work-output low-blade-speed multistage turbines. As a part of this study, the effect of shrouding the third-stage rotor of a three-stage J71 experimental turbine is being investigated. A survey investigation at the equivalent design operating point was conducted on the original version of the turbine (ref. 1), which had only the first- and second-stage rotors shrouded. This reference investigation revealed that (1) the efficiency of the third stage was appreciably lower than that of the first and second stages, and (2) large losses occurred in the hub and tip regions of the unshrouded third stage.

In an effort to improve the tip performance of the third stage and thereby improve the over-all turbine performance, the third rotor was modified to include a shroud. This modified turbine was called the J71-97 turbine. Even though this modification did not improve the over-all performance (ref. 2), it is of interest to determine the effect of the third-stage shroud on the internal-flow conditions of the turbine at the design equivalent operating point. Therefore, this report presents the results of this investigation and compares them with those obtained from the corresponding investigation of the original turbine (ref. 1) in order to determine the effect on the internal-flow conditions of shrouding the third-stage rotor.

SYMBOLS

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A	annular area, sq ft
c	blade chord, ft
D	diffusion factor
p	pressure, lb/sq ft
s	blade spacing, ft
T	temperature, $^{\circ}R$
U	wheel speed, ft/sec
V	absolute gas velocity, ft/sec
W	relative gas velocity, ft/sec
β	relative flow angle (measured from axial direction), deg
γ	ratio of specific heats
η	adiabatic efficiency
ρ	gas density, lb/cu ft
σ	solidity, ratio of actual blade chord to blade spacing, c/s
$\bar{\omega}$	loss coefficient

Subscripts:

av	mass-averaged value
i	inlet
max	maximum
o	outlet
u	tangential
x	axial
0,1,2,3 4,5,6,7	measuring stations (see fig. 1)

Superscripts:

$'$ stagnation or total state

$''$ relative stagnation or total state

APPARATUS, INSTRUMENTATION, AND PROCEDURE

3947 The test installation used for the subject survey investigation of the internal-flow conditions of the J71-97 experimental turbine at equivalent design speed and work is the same as that used for the original turbine and is described in reference 3. The modifications of the turbine geometry, necessitated by the addition of a shroud on the third-stage rotor, are described in detail in reference 2. Briefly, the major change was a reduction of about 2 and 4 percent in the annular flow area through the third-stage stator and rotor, respectively. Figure 2 of reference 2, showing these modifications, is reproduced herein as figure 2. The instrumentation was the same as was used in the original turbine survey and is described in reference 1.

Radial measurements of total pressure and angle were made by the use of combination probes mounted in remotely controlled movable actuators. Measurements were taken at the turbine inlet (station 1, fig. 1) and at the outlet of each succeeding blade row. Data were taken from each of the two actuators at the outlet of each rotor row of blades. Total-temperature measurements were obtained at each rotor outlet by means of spike-type thermocouple rakes, so that readings were obtained at the area centers of 10 equal annular areas. A schematic diagram of the turbine showing the axial and circumferential location of the instruments is presented in figure 1. A photograph of the type of instruments used is presented in figure 3.

The values of static pressure at any measuring station at the hub and tip were obtained by averaging the values measured by the wall static taps on the inner and outer shrouds, respectively. Static pressure at any radius at any given measuring station was determined by assuming a linear radial variation between the hub and tip values. At the outlet of the first and second rotors (stations 3 and 5), however, the static pressure was assumed constant at the value indicated by the wall static taps on the inner shroud. This assumption was made because the indicated wall static pressures on the outer shroud were lower than the hub values, which is in contradiction to the considerations of simple radial equilibrium. These same flow conditions were noted in the investigation of the original turbine (ref. 1). It was felt that these tip values reflected local flow conditions and as such would be meaningless in calculating the mainstream flow velocities.

The survey data were obtained by operating the turbine at the equivalent design speed of 3028 rpm and an equivalent work output (based on torque measurements) of 32.1 Btu per pound. The inlet total pressure and temperature were nominally 35 inches of mercury absolute and 700° R, respectively. Where duplicate measurements of pressure and angle were made behind each rotor, the measurements were numerically averaged at their corresponding radial position. The surveys of the modified turbine and the original turbine of reference 1 were both made near the equivalent design operating point. The values of work output obtained from torque measurements differed slightly, 31.5 Btu per pound for the original compared with 32.1 Btu per pound for the modified turbine. However, it was felt that they were sufficiently close to permit a comparison of the results.

INTERNAL-FLOW CALCULATIONS

<u>Equivalent stage work parameter</u>. - The local work output of a stage is expressed as an equivalent stage temperature drop:

$$\frac{\Delta T'}{T'} = 1 - \frac{T'_o}{T'_i} \tag{1}$$

where T'_e and T'_i are local values evaluated along an assumed streamline passing through a given percentage of annular area at any given measuring station.

<u>Stage and over-all efficiencies</u>. - The local values of turbine stage and over-all adiabatic efficiencies were calculated from

$$\eta_{i-o} = \frac{1 - \frac{T'_o}{T'_i}}{1 - \left(\frac{p'_o}{p'_i}\right)^{\frac{\gamma-1}{\gamma}}} \tag{2}$$

where the local values of both total pressure and temperature are obtained at a given percentage of annular area.

<u>Mass-averaged values</u>. - Mass-averaged values of stage and over-all work and efficiency were obtained from the equation

$$(\quad)_{av} = \frac{\int_0^A (\quad)\rho V_x \, dA}{\int_0^A \rho V_x \, dA} \tag{3}$$

where ( ) indicates the local value of either work or efficiency obtained from equation (1) or (2), and $\rho V_x \, dA$ is the corresponding local value at either the stage or turbine outlet. A numerical integration was used to evaluate the integrals.

Velocities and flow angles. - The local values of total temperature and total and static pressures were used in the one-dimensional
3947 energy equation to calculate the flow Mach numbers and velocities. Components of these velocities V_x and V_u were then determined from the known flow angles. These values, together with the wheel speed U, were used to calculate the relative flow velocities, Mach numbers, and angles.

Loss parameter. - The stage loss parameter, developed in reference 1, is

$$\bar{\omega} = \frac{p_i'' - p_o''}{p_i'' - p_o} \tag{4}$$

Diffusion factor. - A diffusion factor for each turbine blade row was computed from the equation

$$D = \frac{W_{max} - W_o}{W_{max}} \tag{5}$$

where W_{max} is the maximum velocity on the suction surface of the blade and W_o is the average outlet velocity within the plane of the trailing edge.

RESULTS AND DISCUSSION

Stage Work and Efficiency

The variation of stage efficiency η and the stage work parameter $\Delta T'/T'$ with percent of annular area is presented in figure 4. Included in the figure are the over-all and mass-averaged values of the parameters, as well as the variation of efficiency and the stage work parameter obtained from the original J71 experimental turbine investigation (ref. 1).

The mass-averaged values of the work parameter for the first, second, and third stages represent 42.9, 32.3, and 24.8 percent of the over-all turbine work output compared with 44.1, 33.4, and 22.5 for the original turbine. The percent of over-all turbine work output of the first and second stages of the modified turbine has decreased by approximately 1 percent compared with the original turbine. However, the third stage is now producing 2 percent more of the over-all turbine work, representing a 9-percent increase in the stage work. This shift in work division can be attributed to the reduced flow area through the third stage and the fact that the survey data for the modified turbine were obtained at a slightly higher over-all turbine work output.

The mass-averaged values of efficiency for the first, second, and third stages were 0.891, 0.849, and 0.784, respectively. These values were slightly lower (less then 1 percent) than those obtained from the original turbine, indicating that shrouding the third-stage rotor had a negligible effect on stage efficiency. 3947 The spanwise variation of efficiency for the first stage is similar to the trend found in the original turbine. The second stage exhibited greater spanwise variations in efficiency than before. The large variations in efficiency appearing near the hub and tip of the third stage were reduced. From the reasoning set forth in reference 4, it appears likely that the loss regions leaving a blade row may shift both radially and circumferentially for even a small change in operating point or turbine geometry without changing the mass-averaged loss. The data of figure 4 indicate that the loss shifted radially without changing the mass-averaged loss. There might also have been a circumferential shift, but this could not be determined because the probes were located in only one or, at most, two circumferential positions.

The mass-averaged value of over-all efficiency is 0.858, which compares reasonably well with the value of 0.874 obtained at the corresponding turbine operating point from the general performance investigation (ref. 2). The spanwise variation of over-all efficiency also exhibits regions of low efficiency in the hub and tip regions.

Stage Mach Numbers and Flow Angles

The radial variation of absolute and relative Mach numbers and flow angles is presented in figure 5 for both the modified turbine and the original turbine of reference 1. Included are the radial variations of the design values from the velocity diagrams of the original turbine.

Little or no change in the first- and second-stage Mach numbers and flow angles resulted from the third-stage modifications or the increased work output at which the data were obtained (figs. 5(a) and (b)). However, figure 5(c) shows that the third-stage modification caused an increase in the absolute Mach number at the third-rotor inlet and no change in the absolute flow angle. Hence, both the inlet relative Mach number and angle increased. At the outlet of the third-stage rotor, the modification resulted in a reduction of the absolute Mach number and additional turning as the absolute and relative flow angles became more negative.

Stage Loss Function and Design Blade Diffusion

The stage loss function $(\overline{\omega} \cos \beta)/\sigma$ and the design values of suction-surface diffusion D for the stator and rotor blades are presented in figure 6 as functions of annular area. Little change in the level or spanwise variation of loss function occurred in the first and second stages as a result of the modification to the third stage. However, the third stage exhibits a new trend as compared with the original turbine (ref. 1). The large spanwise variations in the loss function
3947 have been reduced through that stage.

The values of diffusion presented in figure 6 do not represent experimental values that actually exist in the turbine. Design diffusion cannot be expected, since the design velocity diagrams were not established at the equivalent design operating point where these survey data were obtained. However, if the design diffusion values are considered as an indication of the actual blade diffusion, then high values of diffusion should indicate high blade losses. No such spanwise correlation is indicated in figure 6 for all three stages. It does appear, however, that, as the level of the stage diffusion increases, the level of the loss function also increases. Arbitrarily, then, the individual stage loss function curves were mass-averaged, and the stage diffusion curves were area-averaged. Figure 7 presents a cross plot of these values. This figure indicates that, as the average design diffusion increased, so did the mass-averaged loss function. The same trend can be noted for the original J71 experimental turbine (fig. 7).

SUMMARY OF RESULTS

The following results were obtained from an investigation of the internal-flow conditions of the J71 experimental turbine when the turbine was modified to include shrouding of the third-stage rotor:

1. The mass-averaged values of efficiency for the first, second, and third stages were 0.891, 0.849, and 0.784, respectively, which are slightly lower (less than 1 percent) than those of the original J71 experimental turbine.

2. The large indicated spanwise variations of both the efficiency and loss in the third stage have been reduced.

3. Design diffusion and blade losses correlated to the extent that high stator and rotor diffusion for the third stage resulted in high losses for the third stage.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, November 3, 1955

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2. Petrash, Donald A., Schum, Harold J., and Davison, Elmer H.: Component Performance Investigation of J71 Experimental Turbine. III - Effect of Third-Stage Shrouding on Over-All Performance. NACA RM E55C29, 1956. 3347

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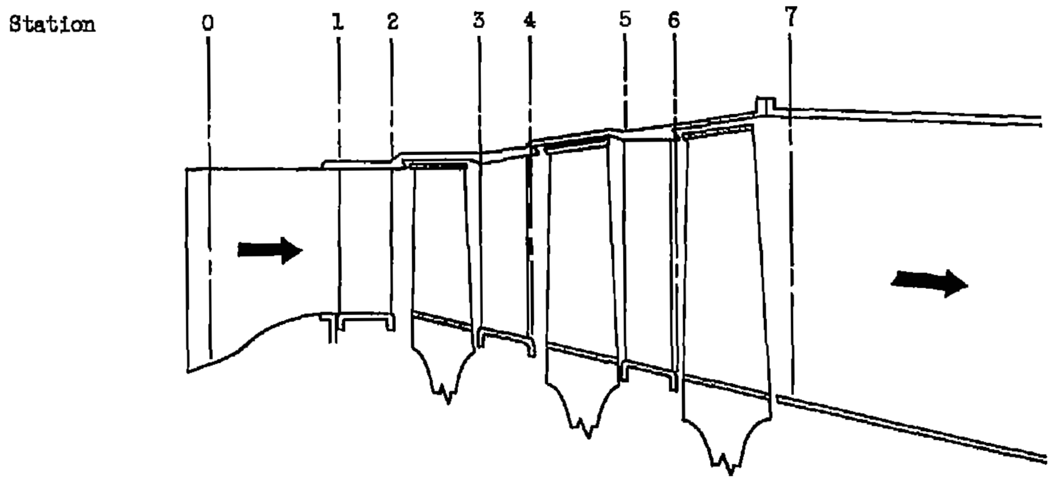
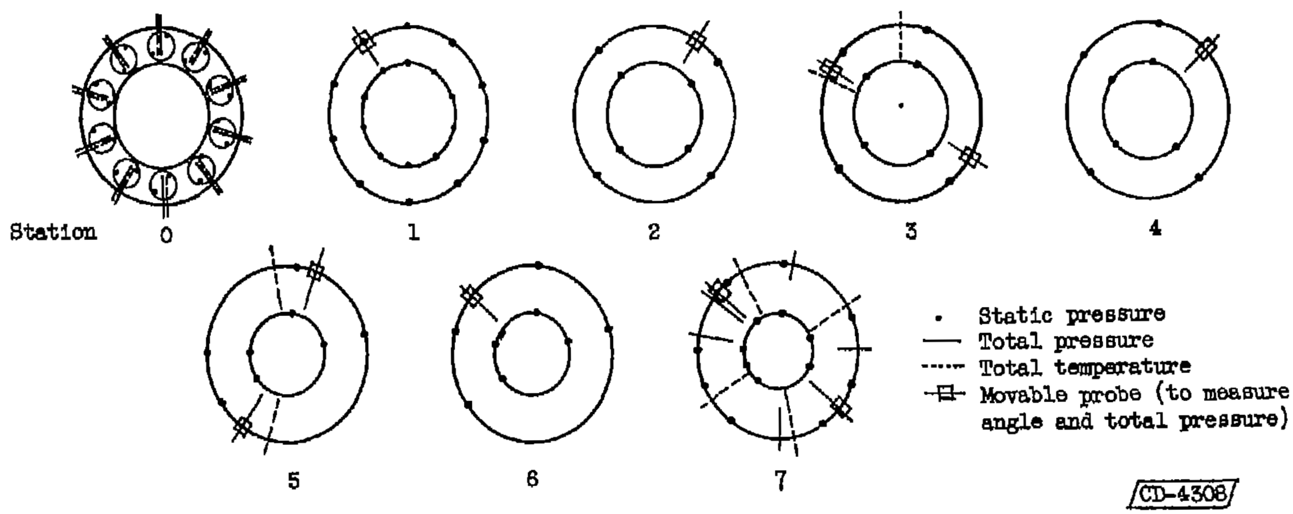
4. Wong, Robert Y., Miser, James W., and Stewart, Warner L.: Qualitative Study of Flow Characteristics through Single-Stage Turbines As Made from Rotor-Exit Surveys. NACA RM E55K21, 1956.



(a) Instrumentions stations.



(b) Circumferential location of instruments at each station.

Figure 1. Schematic diagram of J71-97 turbine showing instrumentation.

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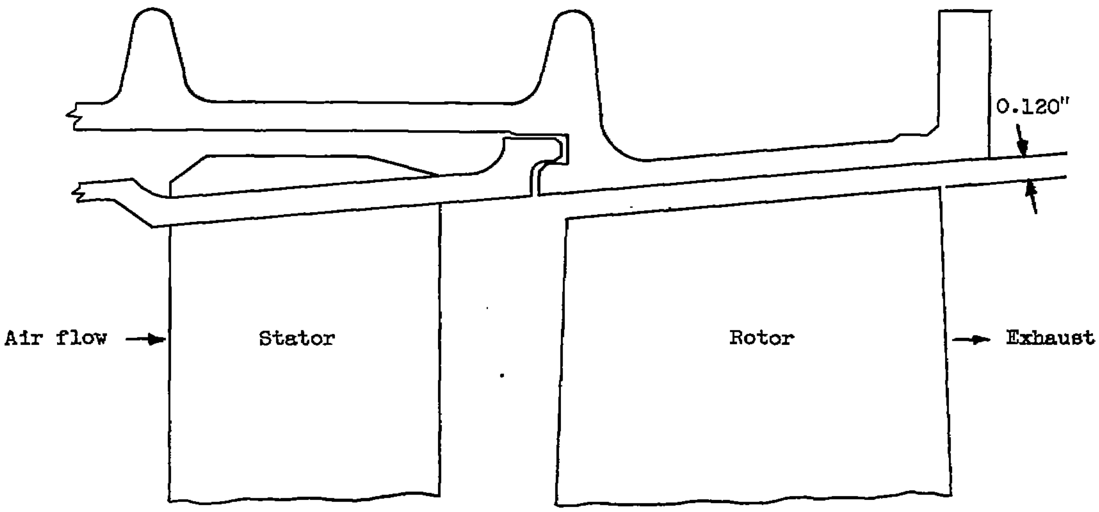
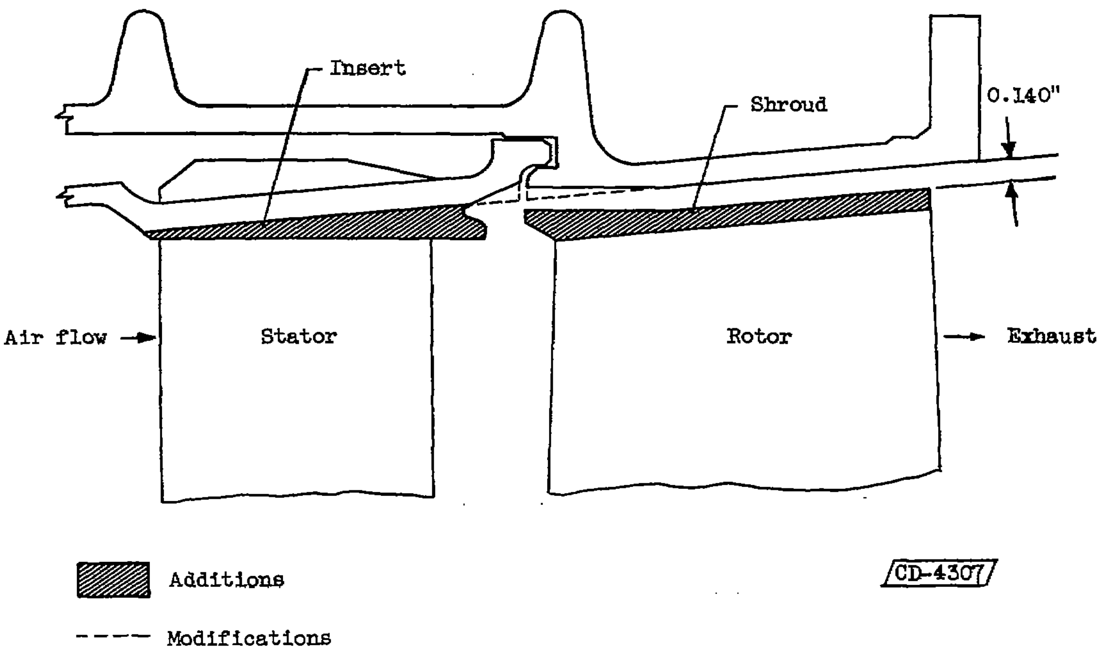
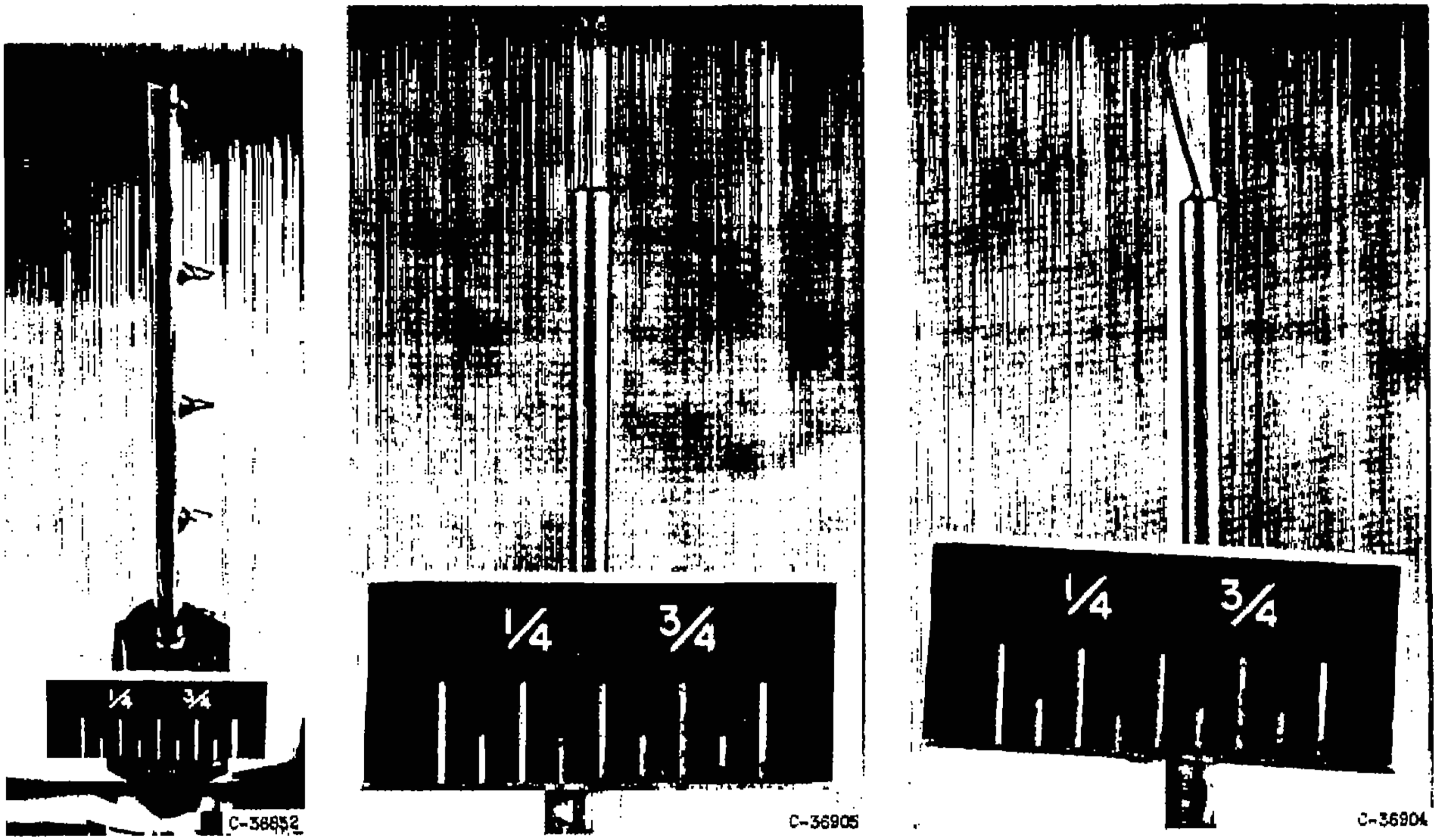


(a) Original unshrouded third-stage rotor configuration.



(b) Shrouded third-stage rotor configuration.

Figure 2. - Schematic diagram of third stage of J71 experimental turbine showing original and modified configurations.



(a) Thermocouple rake.

(b) Total-pressure and angle probe.

Figure 3. - Typical total-temperature rake and probe for measuring total pressure and angle.

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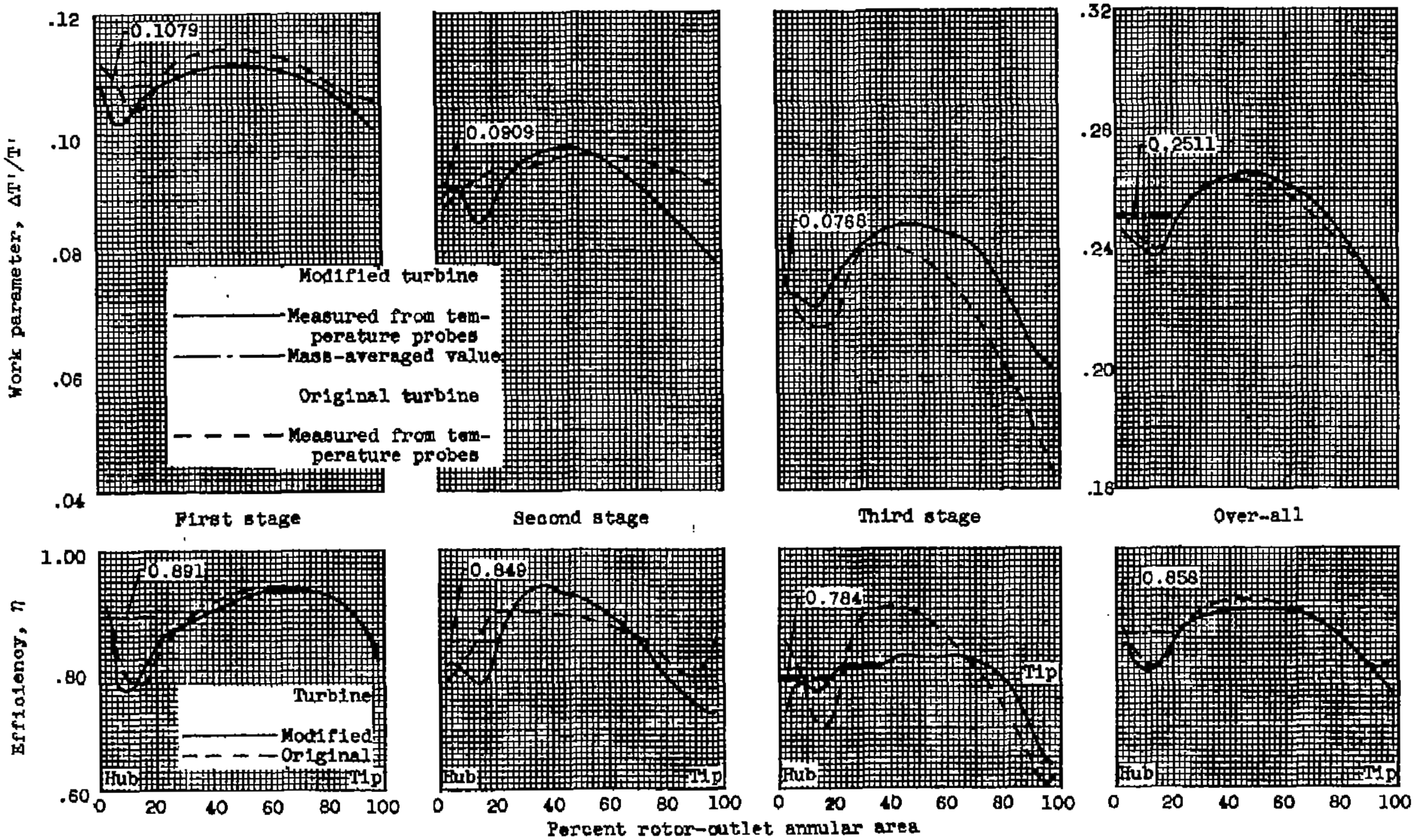
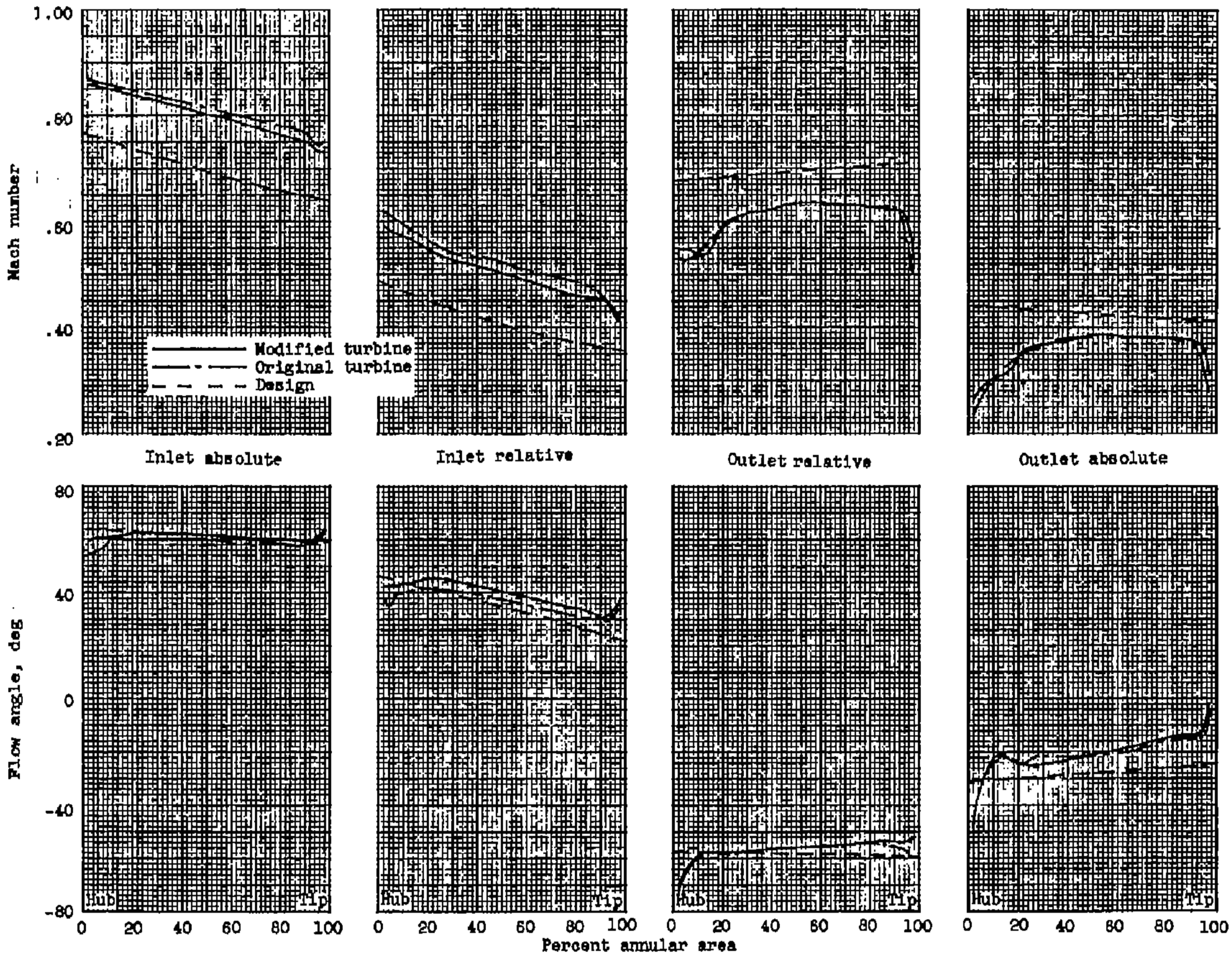


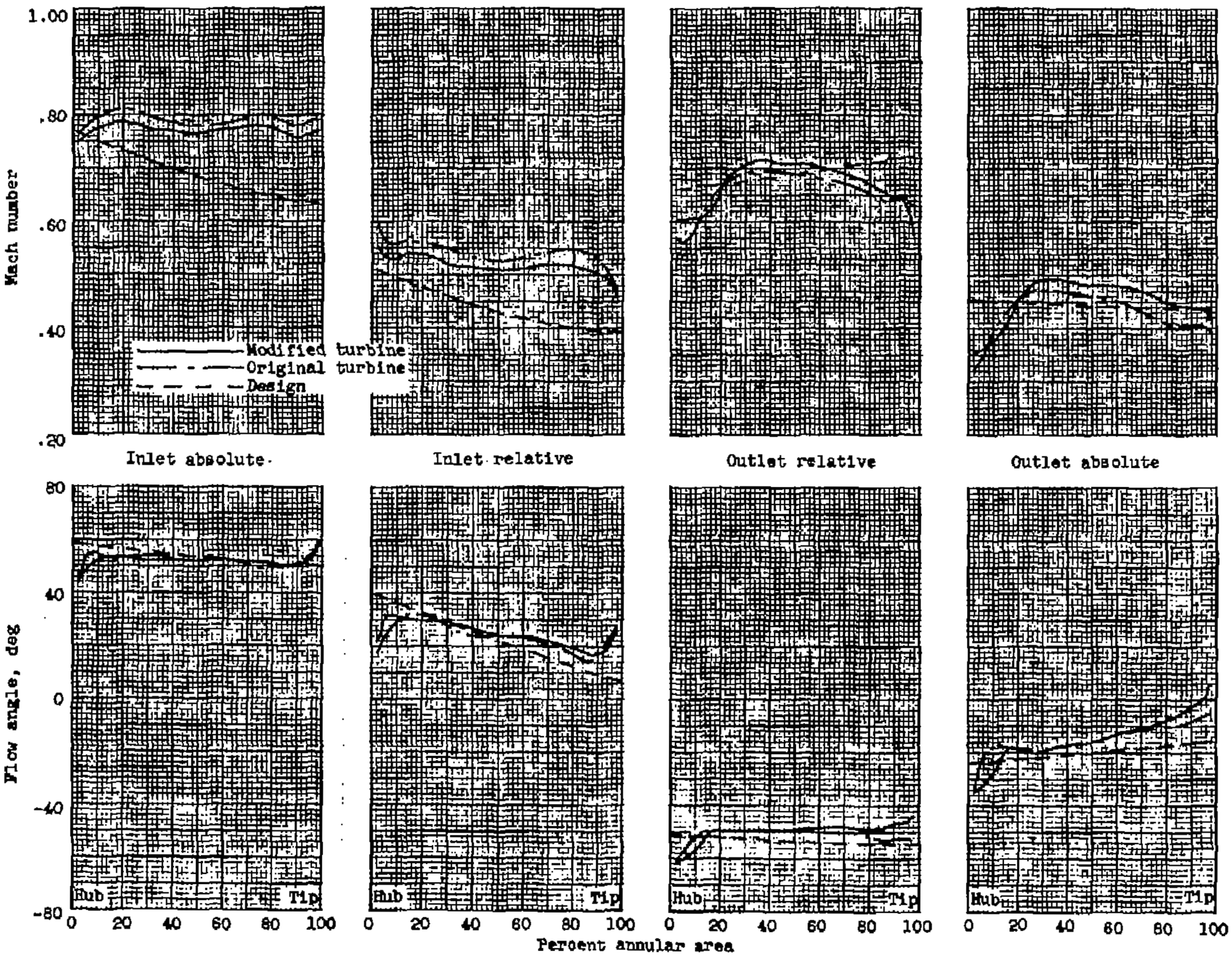
Figure 4. - Variation of stage and over-all work and efficiency with annular area at rotor outlets.

[redacted]



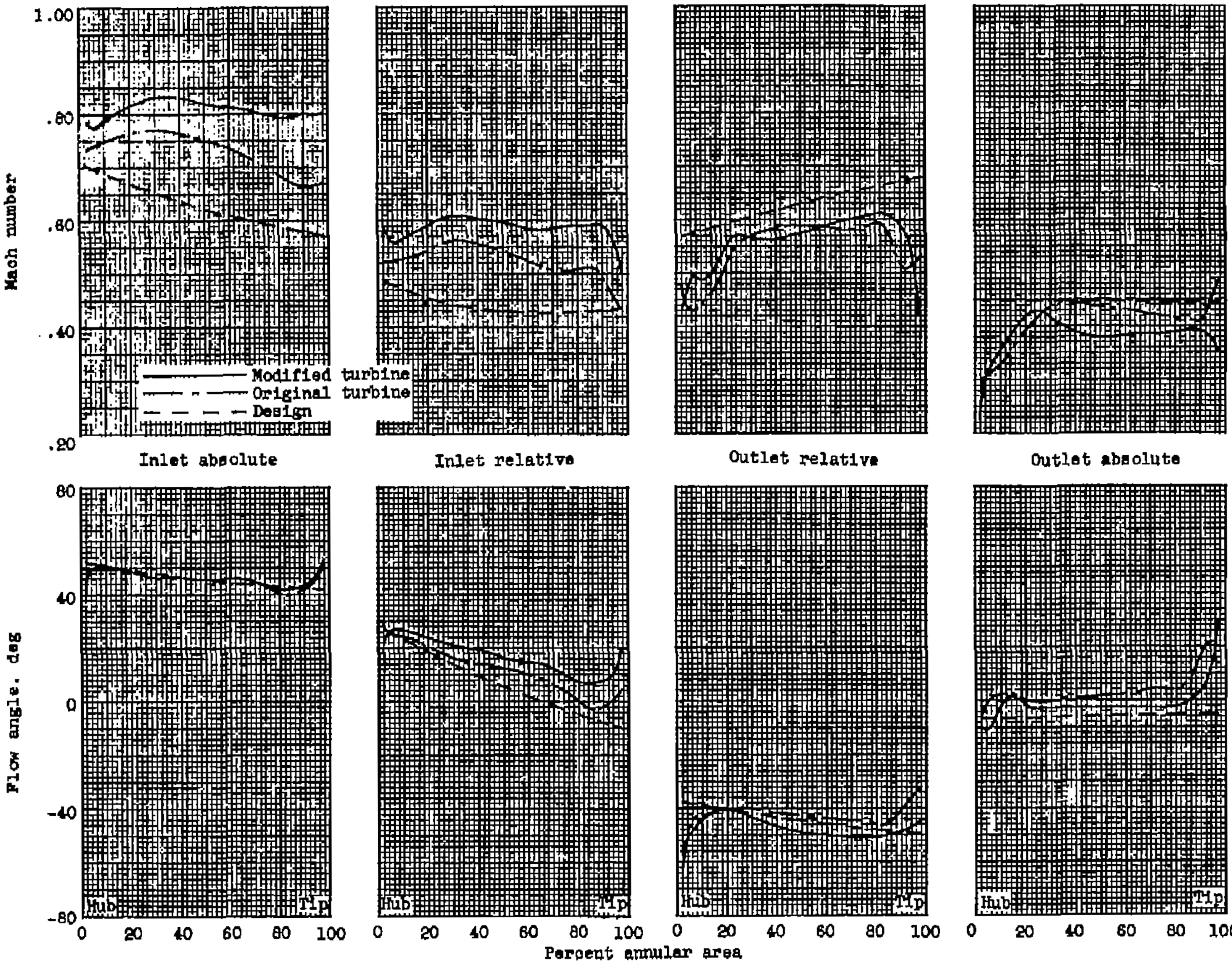
(a) First stage.

Figure 5. - Variation of absolute and relative Mach numbers and angles at rotor inlet and outlet with annular area.



(b) Second stage.

Figure 5. - Continued. Variation of absolute and relative Mach numbers and angles at rotor inlet and outlet with annular area.



(c) Third stage.

Figure 5. - Concluded. Variation of absolute and relative Mach numbers and angles at rotor inlet and outlet with annular area.

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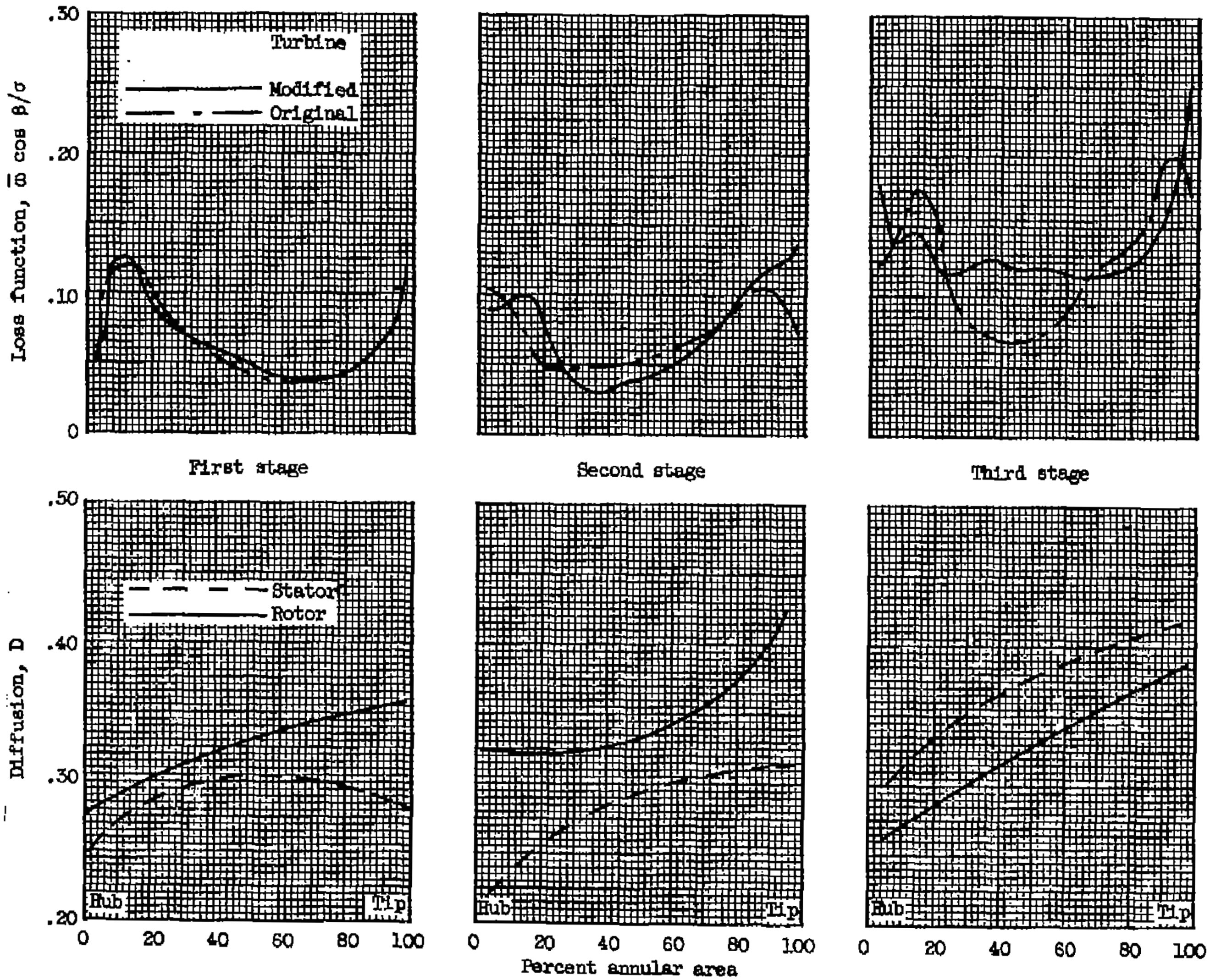

Figure 6. - Variation of loss function and design rotor and stator blade suction-surface diffusion with annular flow area.

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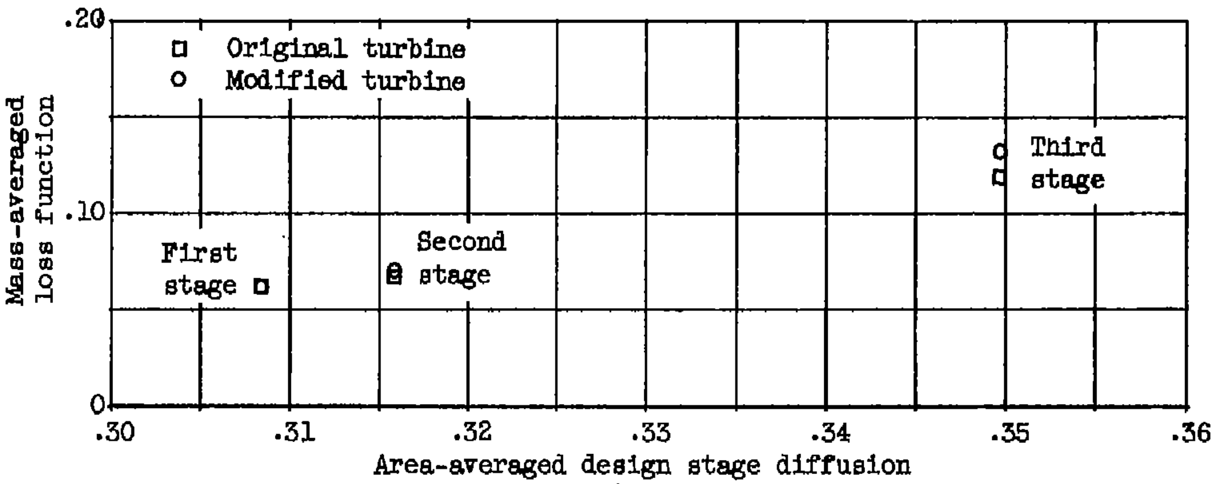

Figure 7. - Variation of average stage loss function and design diffusion.

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